BALLUTE ENTRY, DESCENT AND LANDING ON TRITON

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ABSTRACT

A ballute for entry and descent has been evaluated for the moon Triton of the planet Neptune. A spherical ballute was evaluated, with a surface density of 10 g/m^2 of Kapton that is capable of peak temperatures up to 500°C, radiating on both sides with emissivity of 0.8. An acceptably wide entry corridor was found for deceleration at moderate peak g-load for a range of ballute radii. The mass of a ballute package plus a rocket to cancel terminal velocity is evaluated and compared with the rocket engine and propellant mass for a purely chemical landing. The paper explores the heating rates, temperatures, Knudsen numbers, Reynolds numbers, range and other parameters of the ballute entry for three entry conditions – from a hyperbolic direct or hyperbolic retrograde trajectory, and entry from an initial Neptune orbit. The deployment and release of such a ballute is discussed and the technological readiness level of ballutes in the context of a current NASA program.

1. INTRODUCTION

Triton, a moon of Neptune, is known to have a low-density atmosphere. An atmosphere for Triton was created, based on an occultation that gave a pressure estimate at a certain altitude [1]. For an assumed molecular weight and constant temperature along with published gravitational constant and Triton radius, an atmosphere was constructed consistent with the barometric equation. The present paper evaluates various ballute systems using an atmosphere based on several star occultations and other observations described in [1], specifically a pressure of 2.23 microbar at altitude 48 km and temperature 44 K. By assuming an atmosphere of nitrogen and using the known gravity of Triton, the barometric law is used to evaluate density as a function of altitude. Table 1 describes the Triton atmosphere used in the following analysis.

A ballute entry is evaluated for three entry velocities representing hyperbolic entry into the Neptune system in the 1) direct and 2) retrograde directions, and also 3) entry from a preliminary direct Neptune orbit. The approach speeds (V-Infinity) at Triton are taken to be 2 and 6 km/s for the hyperbolic cases, and 4 km/s for the entry from Neptune orbit, resulting in entry speeds at Triton of 3,807, 5,147 and 6,819 m/s at an altitude of 300 km. Spherical ballutes have been described in the literature [4,5,6] and attached ballutes and towed toroidal ballutes have also been investigated [7,8,9,10].

Table 1 Triton Atmosphere

Altitude, km	Density, kg/m^3
0	6.50E-05
10	5.00E-05
30	2.90E-05
50	1.70E-05
70	9.70E-06
90	5.40E-06
110	3.20E-06
130	1.95E-06
150	1.15E-06
170	7.16E-07
190	4.40E-07
210	2.70E-07
230	1.75E-07
250	1.10E-07
270	7.30E-08
290	4.65E-08
310	3.10E-08
330	1.40E-08
350	9.20E-09

The first proposed use of a ballute for planetary entry, in engineering detail, was in [5] for entry into Venus, where a heavy ballute was used that experienced considerable ablation before being released and deploying a balloon. Their use more generally in aerodynamics was proposed conceptually in the sixties and they were investigated in the seventies for use with the Viking vehicles landing on Mars. However, when deployed from a solid entry vehicle late in the entry in this way, they were rejected as being ineffective. The availability of lightweight film materials like Kapton, in large sheets, has led to proposed modern applications where the ballute radiates the incident aerodynamic heat and can be deployed prior to entry. The entry trajectory with a deployed ballute has markedly less

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heating, which means that the payload for aerocapture or landing requires only limited heat protection, e.g. a multilayer insulation (MLI) thermal blanket. Also the payload can be packaged relatively freely, even allowing for thrusters to be actuated during the aeropass, for example.

The ballute envisioned here has a spherical shape and is attached and integrated into the payload. The ballute is assumed to be made of an inflated thin film enclosed in a net of load-bearing tapes to react to the substantial deceleration or g-loads.

2. TRAJECTORIES

Entry trajectories were evaluated for the three entry speeds indicated above, for three values of ballute ballistic coefficient m/C_dA, kg/m^2, where m is the total mass, C_d is the hypersonic drag coefficient, taken as 0.9, and A is the frontal area of the sphere. It was found that entry angles at altitude 300 km in the range -24 to -38 deg encompassed the desired entry profile of deceleration to near terminal speed for the three ballutes and the three entry speeds. There was a range of entry angle in each case where the vehicle reached nearly the terminal speed at the surface, bounded on the steep side by cases that reached the surface at higher speed, and bounded on the shallow side by cases that escaped from the atmosphere. The results are shown in Table 2.

Table 2 Entry Trajectory Results

m/C_dA, kg/m^2	Entry Speed, m/s	Entry Angle, deg	Speed at Surface, m/s	Peak Stagnation Pressure, N/m^2	Peak g-load, Earth gees	Peak Reference Heating, W/cm^2
1	3807	-20	494	18.0	0.90	0.83
		-30	506	63.0	3.20	1.37
		-32	534	72.0	3.65	1.45
	5147	-24	466	37.0	1.89	2.26
		-32	495	108.0	5.50	3.23
		-34	542	125.0	6.35	3.43
	6819	-26	511	74.0	3.79	5.51
		-32	511	74.0	3.79	5.51
		-34	525	201.0	10.25	7.63
0.5	3807	-18	316	7.8	0.80	0.57
		-32	305	35.0	3.61	1.03
		-40	329	51.0	5.22	1.20
	5147	-22	318	18.0	1.81	0.16
		-32	305	55.0	5.62	2.34
		-40	329	85.0	8.69	2.78
	6819	-24	319	36.0	3.70	3.84
		-32	305	90.0	9.13	5.26
		-40	327	145.0	14.84	6.31
0.25	3807	-18	208	5.2	1.06	0.45
		-32	207	18.0	3.61	0.72
		-40	206	24.0	4.93	0.83
	5147	-20	203	9.2	1.88	1.11
		-32	207	29.0	5.93	1.67
		-40	206	41.0	8.43	1.96
	6819	-22	208	129.0	3.81	2.72
		-32	206	49.0	9.90	3.78
		-40	205	71.0	14.50	4.49

The reference heating is the stagnation point heating rate of a sphere of radius 1 m.
The two values of entry angle shown are the end points of an included range.

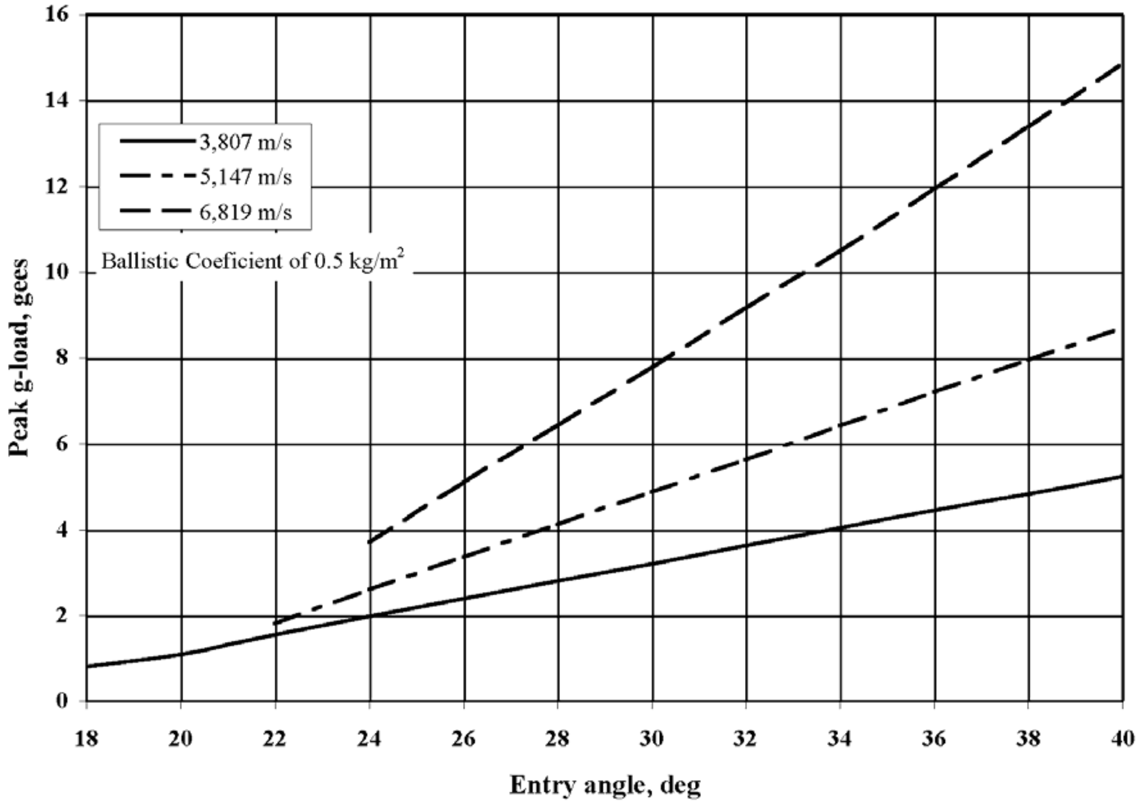

Fig. 1 Peak g-load as a function of entry angle and speed

3. BALLUTE COMPONENT MASSES

The ballute envisioned here is spherical in shape and is attached and integrated into the payload. The ballute is assumed to be an inflated thin film enclosed in a net of load-bearing tapes to react to the substantial deceleration or g-loads. This ballute system has several components – a thin film (e.g., Kapton) ballute to be inflated, a net enclosing the ballute to take the substantial g-loads (e.g. a PBO tape) at a spacing of 1 m around the sphere, a gas tank and a valve to inflate the ballute (e.g. helium), and a landing engine to cancel the near terminal speed achieved by the ballute near the surface. The size and mass of these components were evaluated ballistic coefficients of 1.0, 0.5, and 0.25. The resultant ballute radii were 10.30, 14.57 and 20.60 m for ballute masses of 13.3, 26.7 and 53.3 kg, respectively. The assumed entry mass was 300 kg, and the PBO tape mass was computed on a 1 m net and a stress of 56 kgf on a tape of area 1 mm^2 at 500 C. The landing engine propellant was computed on the basis of a solid motor with I_{sp} = 320 s plus 10% for the case. With these numbers the mass of the system of ballute, net, gas and propellant is as shown Table 3. These numbers do not include SRM casing, radar altimeters and other important equipment.

4. LANDING SYSTEM

The surface approach speed in the range of 200-400 m/s is too large for safe landing and must be reduced prior to impact by firing a main rocket engine, e.g. solid rocket or solid rocket cluster, to take out most of the speed. A small liquid engine, e.g. hydrazine motor, would handle velocity uncertainties due to actual atmospheric density, rocket impulse and ballute drag. Probably the best control would be by use of a radar altimeter. If the motor deceleration is less than that of the ballute acting on itself, the ballute would remain a drag device and could be released during the landing process, to avoid its falling on the lander. Alternatively, a release device could be actuated prior to firing the decelerating rocket.

The path angle at the surface with the ballute alone for these trajectories is about -40 to -80 deg, and the range from entry at 300 km altitude is about 600-1200 km, or about 30-60 degrees of central angle.

Table 3 Ballute System Mass

Ballistic Coefficient, m/C_dA	Entry Angle, deg	Entry Speed, m/s	Ballute Film Mass, kg	He Gas Mass, kg	Tether Mass, kg	Propellant Mass, kg	Total System Mass, kg
1	-24	3807	13.33	0.26	0.72	43.20	57.5
	-28			0.41	1.16	43.70	58.6
	-36			0.69	1.91	58.80	74.7
	-24	5147		0.29	0.81	44.50	59.0
	-32			0.84	2.34	44.60	60.5
	-38			1.21	3.39	64.00	81.0
	-26	6819		0.57	1.61	46.00	61.5
	-32			1.32	8.66	42.00	60.4
	-38			2.02	5.67	66.60	87.6
0.5	-18	3807	26.67	0.80	0.48	28.44	55.7
	-32			0.46	2.17	27.50	56.8
	-40			0.67	3.14	29.60	60.1
	-22	5147		0.23	1.81	28.60	57.3
	-32			0.72	5.62	27.50	58.3
	-40			1.11	8.69	29.60	62.6
	-24	6819		0.47	2.23	28.70	58.1
	-32			1.17	5.51	27.50	60.9
	-40			1.89	8.93	29.40	65.0
0.25	-18	3807	53.33	0.07	0.64	18.72	72.8
	-32			0.23	2.17	18.54	74.3
	-40			0.31	2.97	18.54	75.2
	-20	5147		0.12	1.13	18.54	71.3
	-32			0.38	3.57	18.50	75.8
	-40			0.54	5.07	18.40	77.3
	-22	6819		0.24	2.29	18.60	74.5
	-32			0.63	5.96	18.60	78.5
	-40			0.92	8.73	18.50	81.5

5. APPROACH ACCURACY

In order to avoid skip-out from the atmosphere and avoid excessive g-load and surface speed at the end of ballute deceleration, the entry angle has to be in the range of about -20 to -40 deg. This translates into a radial distance in the aiming plane (the target plane at 90 deg to the approach vector) of about 200 to 600 km, depending on approach speed (V-Infinity) and the ballistic coefficient of the system with the ballute.

6. KNUDSEN NUMBER

For a typical entry (m/C_dA = 0.50 kg/m^2, entry speed = 3807 m/s at altitude 300 km), the mean free path at maximum deceleration (3.2 gees at altitude 87 km, time 144 s) is about 0.012 m. At peak heating (about 0.3 W/cm^2 on the ballute, at altitude 102 km, time 124 s) the mean free path is about 0.018 m, compared with a ballute diameter of 28 m. From this analysis, one can say that the conditions are continuum and the drag and heating values are reasonably accurate.

7. CONCLUSIONS

From the trajectory and system mass results, it can be seen that the smaller ballute, with m/C_dA = 1 kg/m^2, has less film mass but more propellant mass to reduce the surface impact speed, while the largest of the three ballutes investigated, with m/C_dA = 0.25 kg/m^2, has more film mass but less propellant mass, so that the total ballute system mass is about 60 kg (ballute envelope, tether and inflation gas) for each ballute. Adding a solid rocket cluster, a liquid engine and a radar altimeter bring the total deceleration equipment to an estimated 100 kg, which is about one third of the entry mass. If the solid motor decelerates a little too much and actually leaves the lander with an upward speed, it will return under gravity and be landed by the liquid engine governed by the radar altimeter. Possible mass reduction in the ballute may come from an apparent increase of the atmospheric pressure suggested in [1], as well as higher C_d evaluated in [8], and smaller ballute film area that may come from the other shapes analyzed in the references.

8. REFERENCES

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